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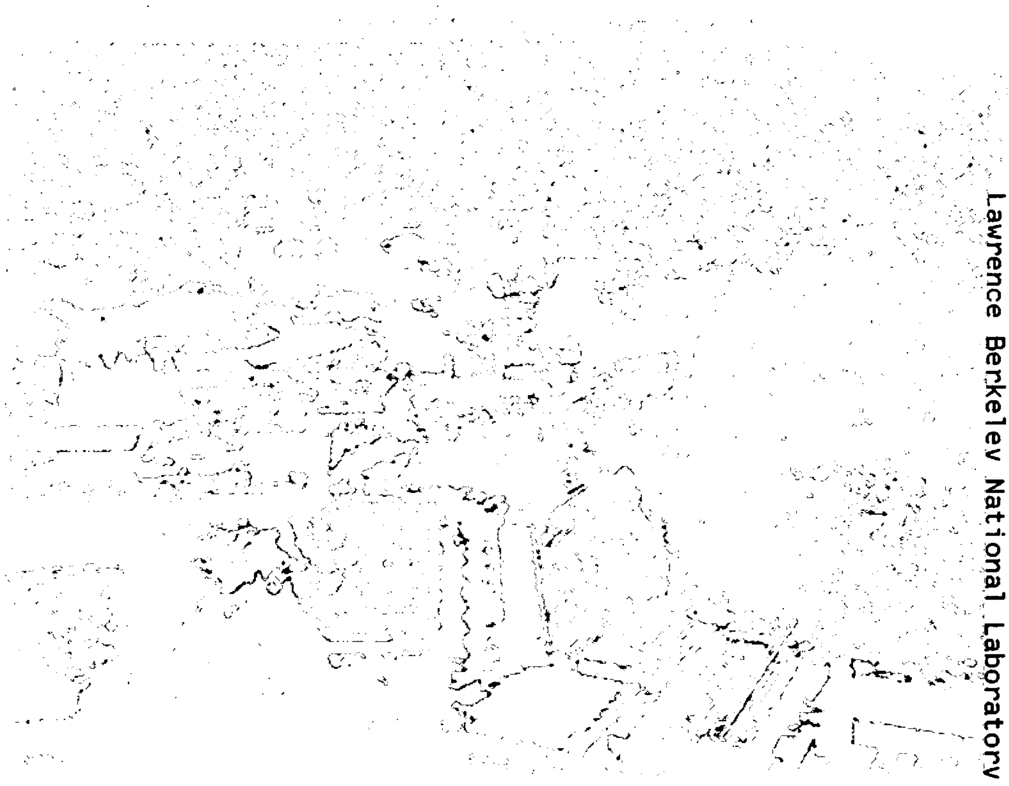

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Global dynamics of the ALS revealed through experimental Frequency Map Analysis

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Frequency Map Analysis is a refined numerical method based on Fourier techniques which provides a clear representation of the global dynamics of a large class of multi-dimensional systems, and which is very effective for systems of 3 degrees of freedom and more. This method was first applied to numerical simulations of physical systems (Solar System, galaxies, particle accelerators,...). Here the results of the same technique are presented, applied directly to the experimental results obtained at the Advanced Light Source (ALS). For the first time, the network of coupling resonances is clearly visible in an experiment, in a similar way as in the numerical simulation. The excellent agreement between numerical and experimental results allow to propose this technique as an effective tool for improving the numerical models and actual behavior of particle accelerators. Moreover, it provides a model independent diagnostic for the evaluation of the dynamical properties of the beam.

I. Introduction. The Advanced Light Source (ALS) is a third generation synchrotron light source located at Lawrence Berkeley National Laboratory [1]. High energy electrons produce synchrotron radiation as they circulate around its 200 meters circumference storage ring. The set of different magnets which are disposed around the ring is the magnetic lattice: dipoles for guiding the electrons, quadrupoles for focusing the electrons, and sextupoles for correction of chromatic aberrations of the electron motion. A closed orbit is a periodic orbit on which a electron arrives after one turn with exactly the same coordinate as when it began. Electrons having initial conditions that are not exactly on the closed orbit will tend to oscillate about the closed orbit. It is important that the magnetic optics are adjusted properly such that the electron motion is stable for particles that have a large displacement from the closed orbit.

There are several reasons for this. First it is desirable to be able to quickly fill the ring with electrons (i.e. high injection efficiency). It is also desirable that the electrons remain in the ring for many hours (i.e. long lifetime). Both the injection efficiency and the beam lifetime are affected by the stability of the electron motion. If the motion of electrons at large amplitudes is unstable, electrons which are scattered to large amplitudes via collisions with gas particles or intrabeam scattering with other electrons may become lost. Similarly electrons that are injected at large amplitude may not be captured. So for high injection efficiency and long beam lifetimes it is necessary that there exist a large stable region in which the electrons will survive.

Similar to other third generation light sources the ALS storage ring is built up of strongly focussing quadrupoles that are required to reduce the beam's emittance. These quadrupole magnets generate large chromatic aberrations that need to be corrected with sextupole magnets. The sextupoles in turn generate geometrical and nonlinear chromatic aberrations, exciting resonances that can make the motion of the electrons unstable. The ALS magnetic lattice is constructed of twelve identical sectors. This 12-fold periodicity helps suppress many nonlinear resonances. Indeed, a resonance occurs when there is an integer relation between the horizontal and vertical betatron tunes ν_x, ν_y, and the longitudinal revolution frequency ν, which is normalized to $\nu = 1$, i.e.

$$N_x\nu_x + N_y\nu_y + R = 0 \qquad (1)$$

where N_x, N_y, and R are integers. However if the lattice is M-fold periodic, its dynamics is the same as the dynamics of a single sector with longitudinal frequency $\nu' = M$. A resonance will occur only when $R = R' \times M$, that is when R is evenly divisible by M (12 in the case of the ALS). So the ALS's 12-fold periodicity is beneficial in suppressing many resonances.

II. Frequency Map Analysis. It is well known that resonances can lead to irregular and chaotic behavior for the orbits of particles, which eventually will get lost by diffusion in the outer parts of the beam, thus reducing its lifetime. It has therefore been a constant concern for accelerator dynamicists to design lattices in order to avoid the resonances of low order ($|N_x| + |N_y|$) which are thought to be the most dangerous. Unfortunately, there is no simple way to forecast the real strength of a resonance without using a tracking code which numerically simulates the evolution of beam particles using a model of the lattice, where each element (quadrupole, sextupole, etc) is represented by a different Hamiltonian of simple form [2]. The difficulty of studying such a non continuous Hamiltonian system is solved by using a surface of section, corresponding to a fixed plane of given location on the lattice ($s = 0$, where s is the longitudinal position), and looking to the return map for this surface of section which is a 4 dimensional symplectic map with position (x, y) and momentum (p_x, p_y) of the beam in both transverse directions as coordinates.

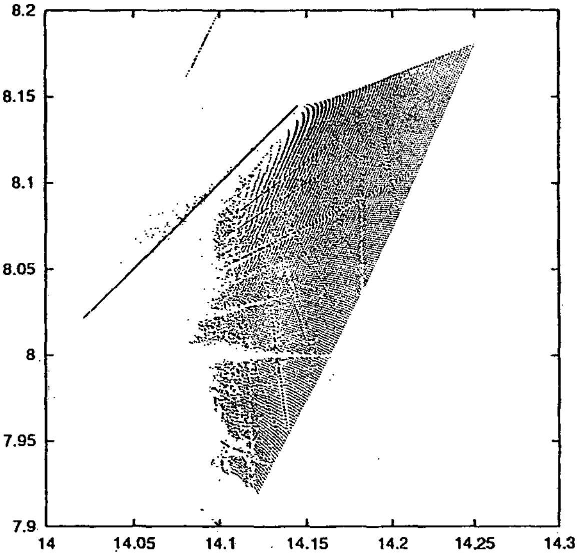

FIG. 1. Frequency map of the ALS for an ideal lattice.

The dynamics of this 4-dimensional symplectic map is analyzed using Laskar's Frequency Map Analysis (FMA) method [3-7]. Briefly speaking, FMA constructs numerically a map from the space of initial conditions to the frequency space. More precisely, two of the initial conditions can be fixed (here $x = y = 0$), and p_x, p_y are taken on a grid of initial conditions. For each selected initial condition (p_{x0}, p_{y0}), the equations of motion of the particle are integrated numerically, and the evolution of the trajectory in the 4-dimensional surface of section $s = 0$ is followed, by recording the values of $x(t), y(t), p_x(t), p_y(t)$ over an interval of time $[0, T]$. Then, using a numerical algorithm (NAFF) based on some refined Fourier technique (see [6]), we search for a quasi periodic approximation of $z_x(t) = x(t) + ip_x(t)$ and $z_y(t) = y(t) + ip_y(t)$ of the form

$$z_w(t) = a_{w0} e^{i\nu_w t} + \sum_{k=1}^{N} a^w_{m_k} e^{i<m_k,\nu>t} \tag{2}$$

where $w = x, y$; $\nu = (\nu_x, \nu_y, 1)$; $m_k = (m_{1k}, m_{2k}, m_{3k})$ is a multi-index; and $< m_k, \nu >= m_{1k}\nu_x + m_{2k}\nu_y + m_{3k}$. If the trajectory is a regular trajectory, KAM theory (see [8]) ensures that $z_w(t)$ is quasiperiodic of the form (2), with fundamental frequencies $(\nu_x, \nu_y, 1)$. In this case, the frequencies can be determined with very high accuracy, as the NAFF algorithm converges asymptotically as $1/T^4$ towards the true values [6]. Thus, on the set $\mathcal{A}$ of initial momentum leading to regular KAM orbits, we can construct the frequency map $F : \mathcal{A} \subset \mathbf{R}^2 \rightarrow \mathbf{R}^2$: $(p_{x0}, p_{y0}) \longrightarrow (\nu_x, \nu_y)$ which associate the fundamental frequencies (ν_x, ν_y) to the initial momentum variables (p_{x0}, p_{y0}) of the corresponding orbit. Moreover, as the numerical algorithm will always give a quasiperiodic approximation of the trajectories, this map F can be defined numerically on the whole space of initial momentum (p_{x0}, p_{y0}). Evidently, on the set of orbits which are not regular, we do not know the behavior of this map, but we are ensured that this map is regular on the set $\mathcal{A}$ of regular initial conditions, or more precisely, as this set is discontinuous, the restriction of the map to $\mathcal{A}$ can be extended in a smooth diffeomorphism $\tilde{F}$ on an open set B of $\mathbf{R}^2$ which coincides with F on $\mathcal{A}$ [6,?]. We are thus insured that when the map F is not regular, the orbits are chaotic, in the sense that they are not KAM quasiperiodic solutions. FMA also allows to measure precisely the diffusion of the orbits in the frequency space [4,5].

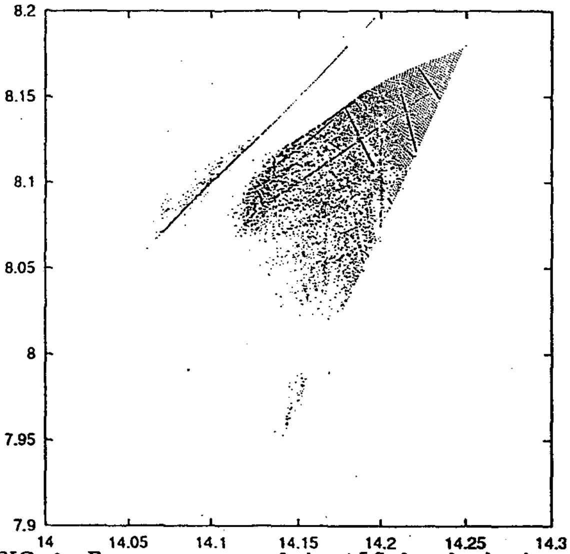

FIG. 2. Frequency map of the ALS for the lattice with measured errors.

For practical use, FMA has the advantage of providing a clear and intuitive view of the global dynamics of the whole phase space of the system. This is illustrated by Figure 1 which represents the image in the frequency plane (ν_x, ν_y) of a grid of initial momentum (p_{x0}, p_{y0}) with tracking over about 1000 turns. In this case, the lattice is supposed to be ideal, that is to have a complete 12-fold periodicity, and the working point, that is the tunes at the center of the beam is (14.25, 8.18). All the lines which appears in this plot are resonant lines which are revealed by the distortion of the frequency map. In the vicinity of these resonant lines appear chaotic zones which correspond to non regular behavior of the frequency map.

Due to errors in the making of the magnets, and various other causes, the machine is usually not perfect, and the existence of these defects will reduce the extent of the regular region, by activating resonances which would only appear with very small amplitude in an ideal machine. Figure 2 gives the image of the frequency map for a realistic case, where the fitted linear (normal and coupling) magnetic errors have been included in the model [10]. It is clear that the stable region in this new model is much reduced with respect to the ideal lattice (Fig.1).

It appears therefore that one of the main issues in particle accelerator dynamics is the search for a model which accurately describes the dynamics of the real machine. This will then open the possibility to compensate for the machine defects and thus to improve its performance. An ideal way to do this is to be able to observe the real dynamics of the beam while the machine is working. Indeed, at the ALS, it is now possible to perform an experimental frequency map which provides for the first time a picture of the global dynamics of the real beam.

The ALS storage ring is equipped with two tools that are necessary for the measurement of the frequency map. The first tool is a set of two fast pulsing magnets termed pinger magnets. Each pinger magnet's pulse time is only 600 ns. This time is less than the time it takes for the electrons to make one turn around the ring. Therefore these magnets can provide a 'single-turn' transverse kick to the electrons. The first pinger magnet (horizontal pinger) provides only a horizontal field. The second pinger magnet (vertical pinger) provides only a vertical field. The amplitude of the horizontal and vertical pinger magnet field can be adjusted independently. Together both the pinger magnets can deliver a variable amplitude 'single-turn' horizontal and vertical kick to the electron beam. The second tool necessary for the measurement of the frequency map measurement is a 'single-turn' beam position monitor (BPM). This BPM measures the transverse center of charge of the electron beam each turn as the beam revolves around the ring. It is capable of storing up to 1024 consecutive turns of data. The BPM can be synchronized to the pinger magnet pulse. In this manner one can record the beam position of the first 1024 turns after the beam is kicked by the pinger magnet.

III. Experimental Conditions. As the charge of a single electron is small, it is not possible to measure its position. During the experiment, the ring is filled with a train of electrons bunches that extend over 1/8th of the ring. The total current is 10 mA which corresponds to 4×10^9 electrons. The beam is kicked by the pinger magnets and the turn by turn position of the center of charge of the electron bunch train is measured by the BPM.

During each experimental run, two sets of measurements are taken. The first set of data is necessary for the calibration of the linear model. The second one is a set of turn-by-turn data for the frequency map. During these measurements, in order to obtain a regularly distributed image, the square of the horizontal and vertical pinger strengths are spaced evenly. The data acquisition time for each point is about 15 seconds, that is about 4 hours for the 600 initial conditions of the frequency map.

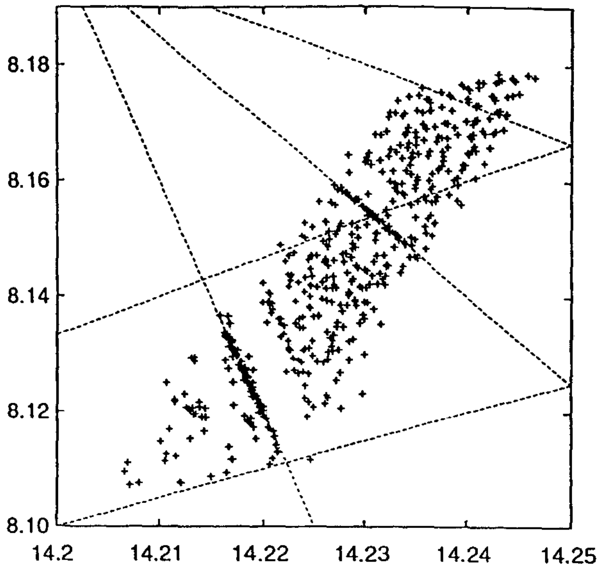

FIG. 3. Experimental frequency map for the ALS with its current settings.

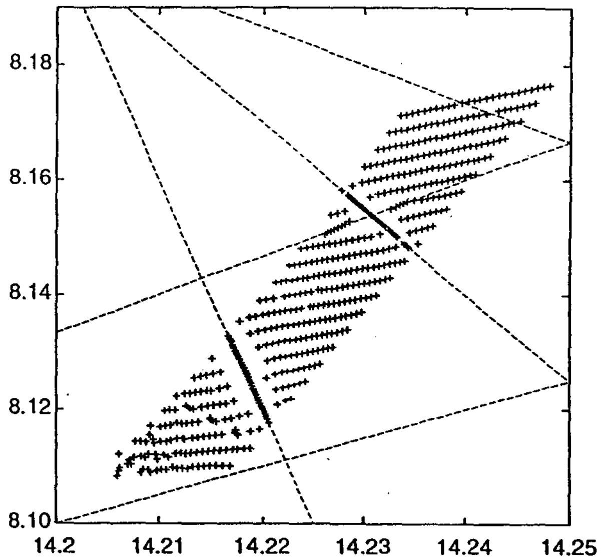

FIG. 4. Simulated frequency map using the same data sampling as in the experiment.

For the first experiment the ALS storage ring was set up close to the nominal condition for operation. The betatron tunes were adjusted to $\nu_x = 14.25$ and $\nu_y = 8.18$. The linear magnetic lattice was measured and adjusted to make it as close to 12-fold periodic as possible. The frequency analysis was made with 25 by 25 initial conditions (Fig. 4). The most striking feature of this plot is the very clear appearance of the two strongly excited coupling resonances of 5th order.

$$4\nu_x + \nu_y + 65 = 0 \quad (3)$$

$$3\nu_x + 2\nu_y + 59 = 0 \quad (4)$$

It is remarkable that these two resonances are 'unallowed' resonances for the lattice. Indeed, they do not show up in the frequency map of the ideal machine (Fig. 1). These resonances are excited by small remaining coupling errors in the lattice that perturb the periodicity of the ring. In order to check the lattice model, we also performed FMA of the numerical simulation with a similar set of initial conditions (Fig. 4). The agreement of the two results: experimental (Fig. 3) and numerical (Fig. 4) is excellent which truly reflects the quality of the adjustment of the lattice model. In the future, we expect to reduce the acquisition time for the experimental frequency map, which could then be used as an interactive online monitor of the quality of the beam dynamics. It will immediately tell us of any unwanted feature of the beam due to destroyed periodicity, or unusual working point.

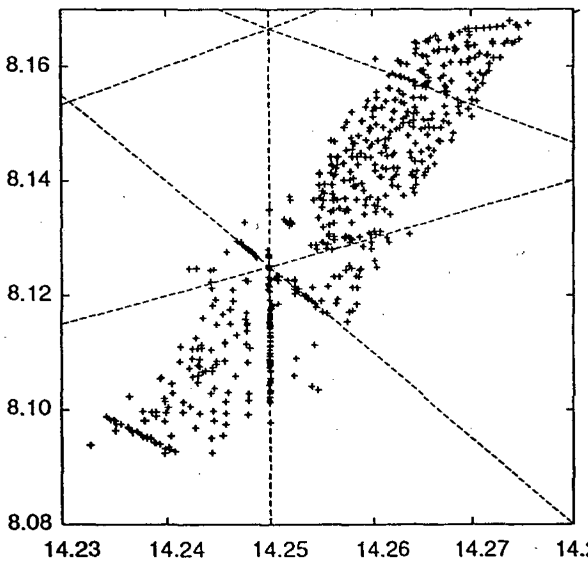

FIG. 5. Experimental frequency map for a previous setting of the ALS.

As an illustration we set up the beam to a different working point ($\nu_x = 14.275, \nu_y = 8.167$). In this case, the experimental frequency map (Fig. 5) shows several unwanted resonances intersecting at ($\nu_x = 14.25, \nu_y = 8.125$). This intersection of active resonances will induce some rapid diffusion of the particles with subsequent decrease of the performances of the machine. Indeed, we observed significant beam loss at this intersection during the experiment. It is clear that after the observation of such a behavior, one should either find some way to reduce the amplitude of the resonances by improving the periodicity of the lattice, or change the working point to another location. In fact, this working point was the designed ALS working point where the machine was operated for several years. With this setting, the injection efficiency was somewhat erratic while the reason for this was not clearly understood at the time. The working point was changed to the present one after the observation of the FMA of a previous numerical model of the lattice [7].

IV. Conclusions. There has already been some attempts in accelerator physics to use BPM data [] and to relate FMA to measured frequencies [12,13], but to our knowledge, we have presented here for the first time through an experiment the full network of coupling resonances occuring in such a dynamical system of 3 Hamiltonian degrees of freedom. This experiment demonstrates in a clear way the complexity of the dynamics of such a system which cannot be reduced to simple resonances of two degrees of freedom systems. It stressed the importance of the understanding of the subtle behavior encountered in dynamical systems of truly 3 degrees of freedom (see [4] and references therein).

On the other hand, it is remarkable that the numerical model (which is relatively simple) agrees so well with the observed dynamics. It can then be used effectively for simulation of modifications of the lattice, like insertion of new devices. We are convinced that the acquisition time for the experimental frequency map can be decreased by a large amount, and that this technique can be used in the future as a regular maintenance device for the ALS and similar machines.

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